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The burst behavior of the eclipsing low-mass X-ray binary MXB 1659–298

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ABSTRACT

We present a detailed study of the correlations between the burst properties and the inferred mass accretion rate for the X-ray transient MXB 1659–298. The bursts which exhibited oscillations were observed when the source was at relatively high mass accretion rate, similar to what has been seen for other sources. However, due to the limited number of observations at lower mass accretion rates, no bursts were observed at such accretion rates and it is still possible that when MXB 1659–298 accretes at such low mass accretion rates, bursts can occur which might still exhibit burst oscillations. No clear correlations were found between the different burst properties and accretion rate, in contrast to what has been found for KS 1731–260 and 4U 1728–34, but similar to what has been reported for Aql X-1. However, this lack of correlation for MXB 1659–298 and Aql X-1 might be due to the limited range of mass accretion rate observed for those sources compared to KS 1731–260 and 4U 1728–34.

Subject headings: accretion, accretion disks — stars: individual (MXB 1659–298)— stars: neutron — stars: rotation — X-rays: stars — X-rays: bursts

1. Introduction

Using the proportional counter array (PCA) on board the *Rossi X-ray Timing Explorer* (*RXTE*), nearly coherent oscillations (or burst oscillations) have now been found in nine[5] low-mass X-ray binaries (LMXBs) out of the more than fifty systems that exhibit type-I X-ray bursts

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(see, e.g., Strohmayer 2001 for a review about burst oscillations). The properties of these burst oscillations (coherence, strength, amplitude, stability) suggest that they are most likely due to the spin of the neutron star (e.g., Strohmayer, Zhang, & Swank 1997a; Strohmayer et al. 1996, 1998a, 1998b; Strohmayer & Markwardt 1999; Muno et al. 2000). The behavior of the burst oscillations is complex and often their frequency increases during the decay of the burst (e.g., Strohmayer et al. 1996; although a decreasing trend in certain bursts have been reported by Strohmayer 1999, Miller 2000, and Muno et al. 2000). This increase is usually explained by assuming that at the start of the burst the burning layer expands by several tens of meters, causing the burning layer to slow down. Later on in the burst, this layer relaxes back to the neutron star surface and spins up again (see, e.g., Strohmayer et al. 1996). Recent theoretical calculations pointed out that the theoretical expected values of spin-down (assuming rigid rotation) are a factor of at least three smaller than the frequency shifts observed (Cumming et al. 2001; see also Cumming & Bildsten 2000; see, however, Spitkovsky, Levin, & Ushomirsky 2001).

Clearly, the physical mechanism behind the burst oscillations and their frequency evolution is still not well understood. Also, it is not clear how the behavior of the burst oscillations is influenced by the other properties of the bursts (e.g., the burst profile, episodes of radius expansion) or with the other properties of the source (i.e., the variations in the mass accretion rate ($\dot{M}$) onto the neutron star surface). Recently, progress has been made in our understanding of the correlations between the burst oscillation behavior and other burst and source properties. However, the situation is complex and so far a consistent picture, valid for all sources, has not yet emerged.

1.1. Previous studies

The accretion rate in neutron-star LMXBs is usually inferred from the position of the sources in their X-ray color-color diagrams (CDs) or hardness-intensity diagrams (HIDs). The low-luminosity sources trace out an atoll-like shape (hence the name atoll sources), with the different branches referred to as the banana branch (high inferred accretion rate) and the island state (low inferred accretion rate; see Hasinger & van der Klis 1989 for the classification of the different types of neutron star LMXBs). The changes in the burst properties as a function of mass accretion rate has been studied before by several others (e.g., van der Klis et al. 1990), however, we will only summarize here the recent *RXTE* work about correlating the burst oscillations with other burst properties and the source accretion rate. We refer to Muno et al. (2000) for an elaborate description of pre-*RXTE* work. Muno et al. (2000) extensively studied the behavior of the bursts and their oscillations with variations in the inferred mass accretion rate (using a CD) for the X-ray transient KS 1731–260. It was found that when this source was on its banana branch (high inferred $\dot{M}$) that the X-ray bursts typically had short decay times, were relatively bright, demonstrated clear episodes of radius expansion (RE), and exhibited burst-oscillations. In contrast, when the source was in its island state the bursts had longer decay times, were weaker, showed no evidence for RE, and no burst oscillations could be detected. Muno et al. (2000) identified the banana branch

bursts (with burst oscillations) as occurring in a helium-rich environment and those in the island state (without burst-oscillations) occurring in an environment which has a considerable amount of hydrogen mixed in. The theoretical study of Cumming & Bildsten (2000) is consistent with these findings, in the sense that large amplitude oscillations are more likely to be observed in pure He-bursts than for mixed H/He-bursts.

Two other sources have been similarly studied: 4U 1728–34 (Franco 2001; van Straaten et al. 2001) and Aql X-1 (Fox et al. 2001). However, different correlations were found between the burst properties and variations in the mass accretion rate. As with KS 1731–260, the bursts observed for 4U 1728–34 did not exhibit oscillations at low inferred $\dot{M}$, but only at larger $\dot{M}$ (Franco 2001; van Straaten et al. 2001). Moreover, not only are the burst oscillations present only above a certain mass accretion rate, their strength increases with $\dot{M}$ (Franco 2001). Unlike KS 1731–260, an anti-correlation was found between the presence of RE episodes during the bursts and $\dot{M}$, with not all bursts which exhibited oscillations also experienced RE episodes. A final difference is that the brightest bursts occurred on the banana branch for KS 1731–260 (Muno et al. 2000) but in the island state for 4U 1728–34 (Franco 2001; van Straaten et al. 2001).

Despite the fact that both sources behave differently with respect to variations in mass accretion rate, for each source individually the burst behavior seems to be correlated with $\dot{M}$. However, the results obtained for Aql X-1 (Fox et al. 2001) demonstrates that such correlations are not always observed. Only a limited amount of data were obtained during the island state of this source and no X-ray bursts were observed in this state; all bursts occurred at relatively high mass accretion rate. The detection of burst oscillations during one of these bursts is consistent with the findings that bursts oscillations tend to occur preferentially at high mass accretion rates. However, both bright and less bright (factor of 2 dimmer) bursts occurred on roughly the same position in the CD, thus at roughly the same mass accretion rate. The same is true for bursts with and without RE episodes. The only burst exhibiting oscillations has a clear RE episode, but a very similar burst which also exhibited a RE episode showed no burst oscillations. Clearly, currently the burst behavior of Aql X-1 does not seem to be very well correlated with the average mass accretion rate of the source just prior to the onset of the bursts (Fox et al. 2001). However, we note that for Aql X-1 only a limited amount of burst were observed and only at a limited range of inferred mass accretion rate. Better and clearer correlations might be observed when more bursts at a larger range of accretion rates are observed for this source. These three above discussed *RXTE* studies, when combined with the previous studies done with data obtained with other satellites (see, e.g., Lewin, van Paradijs, & Taam 1993 for an overview), demonstrate that presently no standard picture which is valid for all sources exist regarding the correlation between the burst behavior and the average mass accretion rate.

Very recently, it has been found (Muno et al. 2001) that the burst oscillations observed for the systems with relatively high burst-oscillation frequency (∼500–600 Hz) are almost always observed during RE bursts, whereas the burst oscillations for the systems with low frequencies (∼300 Hz) are approximately equally found among bursts with and without RE episodes. Muno et al. (2001)

suggested that this might indicate that the burst properties change differently as a function of $\dot{M}$ in the systems with high or low frequencies. To increase the number of sources (exhibiting burst oscillations) for which the burst properties are correlated with the mass accretion rate, we have undertaken a similar study for the bursting LMXB MXB 1659–298.

1.2. MXB 1659–298

This system was first discovered by Lewin, Hoffman, & Doty (1976). Type-I X-ray bursts were reported from the system, demonstrating that the compact object is a neutron star. The source exhibits periodic X-ray dips and eclipses with a period of ∼7.1 hours, which can be identified with the orbital period (Cominsky & Wood 1984, 1989). In April 1999, the source was detected after more then twenty years of quiescence (in 't Zand et al. 1999). Observations of the source were obtained with the proportional counter array (PCA) on board the *RXTE* (e.g., Wachter, Smale, & Bailyn 2000; Wijnands, Strohmayer, & Franco 2001), with *BeppoSAX* (Oosterbroek et al. 2001), and with *XMM-Newton* (Sidoli et al. 2001). With these observations, an updated orbital ephemeris was obtained by Wachter et al. (2000) and Oosterbroek et al. (2001). Fourteen X-ray bursts were found in the *RXTE* data and burst oscillations were discovered in eight of them with a frequency of ∼567 Hz (Wijnands et al. 2001). Here we report on the behavior of burst oscillations with respect to the other burst properties (e.g., radius expansion bursts, rise time scales) and the burst properties with respect to the variations in the mass accretion rate onto the neutron star surface.

2. Observations and analysis

We used all currently available archival data for our analysis. Data were obtained in the Standard 1 and 2 modes, and simultaneously using an event mode (E_125us_64M_0_1s; 122 μs in 64 photon energy channels covering the full *RXTE*/PCA energy range of 2–60 keV). The Standard 1 data (1/8 s time resolution and 1 energy channel) were used to study the profiles of the bursts. The Standard 2 data (16 s resolution; 129 channels) were used to create the color-color diagram (CD) and hardness-intensity diagram (HID) of the source. As the soft color we used the count rate ratio between 4.1–7.5 keV and 2.9–4.1 keV, and as the hard color the ratio between 11.4–18.8 keV and 7.5–11.4 keV. We have also made those diagrams using different colors (although the limiting spectral resolution of *RXTE*/PCA does not allow many variations of the colors), but the colors used here gave diagrams which showed the different tracks the best. The event mode data were used to calculate 1/16–4096 Hz power spectra which were used to investigate the rapid X-ray variability of the source. The same data were also used to analyze the spectral evolution during the bursts.

3. Results

3.1. The long-term behavior of the source

We used the quick-look, one-day averaged *RXTE* All Sky Monitor (ASM) data[6] to determine the long-term X-ray light curve of the source (Fig. 1). The source was dormant for the first ∼1000 days of the *RXTE* mission but became active in April 1999 (in 't Zand et al. 1999). The initial part of the outburst can be characterized by a faster rise (<50 days) and slower decay time scale (>100 days), however, instead of going back into quiescence, the source exhibited a second outburst which continues until the end of July 2001, after which the source started to decay again. It become undetectable in the ASM around the end of August 2001. A pointed observation with the *RXTE*/PCA on 7 September 2001, showed that the source could still be detectable at a level of ∼5 mCrab (2–60 keV), however, later observations on 14, 24, and 30 September 2001 showed that the source could not be detected with upper limits of 0.5–1 mCrab. In Figure 1, we indicated when the *RXTE*/PCA observations used in our analysis were performed. As can be seen, most of the data were obtained when the source was at relatively high count rates, and only a few observations were performed when the source was weaker.

3.2. The variations in the mass accretion rate

To correlate the burst behavior with the accretion rate, we have created a CD and HID for MXB 1659–298. However, because of the X-ray dips and the eclipses, those diagrams are dominated by the very large spectral variations during those events. Including those events the diagrams were heavily contaminated and not useful to determine the exact spectral state of the source. Therefore, we decided to manually remove all the data obtained during the dips or the eclipses (i.e., we removed the data for which the count rate variations clearly showed that the source was exhibiting dips or eclipses). The resulting CD and HID are shown in Figure 2. Clearly visible are two branches in the diagrams, reminiscent of the atoll-shaped track of other low-luminosity neutron star LMXBs; the lower branch can be identified with the banana branch and the upper with the island state. The rapid X-ray variability on the banana branch was weak (several percent rms), as expected on this branch (Hasinger & van der Klis 1989). The variability could not be accurately determined in the island state due to the very low count rate and limited amount of data obtained in this state. However, the typical upper limits on the noise properties during this state (>20% rms) are fully consistent with the expected timing properties for this state. This behavior clearly demonstrate that MXB 1659–298 can be classified as an atoll source.

In Figure 2*a*, we indicated (by numbers; see Wijnands et al. 2001 for the numbering of the

[6]The quick-look data can be obtained from http://xte.mit.edu/ASM_lc.html and is provided by the ASM/*RXTE* team. See Levine et al. (1996) for a detailed description of the ASM.

bursts) when the bursts occurred. To estimate the source colors during the time of the bursts, we used 256-s of data just prior to them. We only show the bursts which occurred outside the X-ray dips and the eclipses, because the colors of the other bursts are strongly affected by the spectral variations during those events. However, only very limited amount of data were obtained during the island state and no bursts were observed during the time the source was in this state; therefore, all bursts so far observed in MXB 1659–298 occurred when the source was on the banana branch, at relatively high inferred mass accretion rate (see also Muno et al. 2001).

There is no clear correlation between the position of the source on the atoll track at the time of the bursts and the presence (burst 2, 3, 4, 8, 11) or absence (burst 6, 7, 13) of burst oscillations (Fig. 2 *a*). Both bursts with and without burst oscillations occurred at approximately similar locations in the CD. Similarly, one of the two bursts (burst 2) with the burst oscillations occurring only during the rising phase, occurred at approximately the same positions in the CD as one of the bursts which exhibited the burst oscillations during their tail (burst 4).

We also calculated the fluxes of the persistent emission (excluding the dips and eclipses) just prior to the bursts. The spectra were derived from the top Xenon layers of whichever detector (or proportional counter unit [PCU]) was on during the observations. Background subtraction and the creation of the response matrices were performed using the standard techniques and FTOOLS version 5.04. We fitted different functions to the spectral data, but the obtained fluxes were very similar. We quote the obtained absorbed fluxes in Table 1. No correlation was found between the burst properties and the 3–25 keV flux.

3.3. Extra bursts

We report the detection of two extra bursts which were missed[7] by Wijnands et al. (2001; Fig. 3). No oscillations could be detected during these bursts. Remarkably, they happened within only $\sim$50 seconds of each other. Secondary bursts occurring $<$10 minutes after the primary bursts have been reported before in several sources (see, Lewin et al. 1993 for a discussion), which are thought to be due to unstable burning of residual fuel which did not burn during the primary bursts (see, e.g., Fujimoto et al. 1987). A similar explanation might be valid for what we see for MXB 1659–298, although a recurrence time of 50 seconds is very short. Sadly, detailed investigations of these bursts (e.g., their spectra) are hampered by the fact that they occurred during the X-ray dips (Fig. 3). Therefore, we do not discuss these bursts further in our paper.

[7]They were missed because of the large bin size (16 s) used by Wijnands et al. (2001) to search for bursts, which is considerably longer than the bursts duration. In the present study, we used a bin size of 1/8 seconds which makes it unlikely that any more bursts are missed.

3.4. Burst profiles

The burst profiles of the bursts discussed in this paper (excluding those that occurred when the source was dipping or eclipsed) are shown in Figure 4. From this figure it can be seen that the bursts in MXB 1659–298 exhibit a wide variety of bursts profiles. To quantify their behavior, we have determined the rise time ($t_{\rm rise}$, defined as the time it takes for the flux to increase from 25% to 90% of the peak flux) and the decay time of the bursts ($t_{\rm decay,1}$ and $t_{\rm decay,2}$, defined as the exponential decay time; note that two successive exponential functions were needed to fit the decay in the tail of the bursts correctly, similar to what has been observed for, e.g., KS 1731–260 by Muno et al. 2000, and Aql X-1 by Fox et al. 2001). The rise and decay times are listed in Table 1. The bursts can be divided in two groups; one with rise times shorter than 0.7 seconds, and the other with rise times between 1 and 2 seconds. The two groups of bursts in terms of their rise time seems to be correlated with the burst oscillations occurring either in the tail or in the rise. Bursts 3, 4, and 8 have all a rise time of 0.5–0.6 second *and* exhibit burst oscillations in the tail of the bursts; bursts 2 and 11 have rise times of 1.0 and 1.4 seconds, respectively, and both show oscillations during the rise of the bursts only.

Although this correlation seems to be strict, the two groups also contain bursts which do not show oscillations. Burst 7 also has a short rise time (0.7 seconds), but no oscillations have been detected in this burst (i.e., not in the tail as might be expected). Wijnands et al. (2001) already pointed out that this burst has a unusual excess in burst flux about 4 seconds after the burst peak, which is not apparent for the other bursts which have short rise times (Fig. 4). This burst flux excess occurs at approximately the same time as when the burst oscillations are expected to appear (as judged from the similar bursts 3, 4, and 8). The spectral properties of this burst (see § 3.5) do not show any obvious change at the time of the occurrence of this burst flux excess (Fig. 8 *top right*).

In addition to burst 7, bursts 6 and 13 also do not exhibit oscillations. It is intriguing that those bursts have the longest rise times of all bursts in our sample (2.0 and 1.7 seconds, respectively). Another remarkable fact about burst 6 is that it is the weakest burst in our sample. This might be related to the fact that this burst occurred only about two hours after the previous burst (see Fig. 5; burst 5 occurred during dipping activity and is not discussed in detail in this paper). However, this might also be unrelated, because regular bursting of MXB 1659–298 with a interval time of ∼2.5 hours had been observed before (Lewin et al. 1976). Burst 13 is the longest burst in our sample: besides the long rise time, the burst has a very long decay time ($t_{\rm decay,1} \sim 3$, $t_{\rm decay,2} \sim 15$). Besides the unusual profiles, burst 6 and 13 are the only bursts in our sample which do not show evidence for RE episodes (§ 3.5). These unusual properties of these two bursts might be related to the fact that they do not exhibit burst oscillations, but the number of bursts is too small to make definite conclusions and a chance coincidence cannot be ruled out.

3.5. The burst properties

We produced energy spectra for the bursts for each 0.25 second interval from the event mode data. Once more, the bursts during the dips and eclipses are left out of our analyses because their spectral parameters are heavily contaminated by those events and no reliable information about the intrinsic spectral behavior of those bursts could be obtained. As background we used 15 seconds of data prior to each burst. This assumes that the occurrence of the bursts did not effect the overall properties of the persistent emission, which most likely is an over-simplification of the situation. However, the procedure is standard for analyzing the spectral evolution of bursts and other, more complicated procedures give very similar results (see, e.g., Muno et al. 2000 and Kuulkers et al. 2001 for a discussion). We fitted the spectra between 2.5–20 keV with an absorbed blackbody (the column density used was fixed to 0.7×10^{22} cm^{-2}, which was the mean value obtained from fits using a variable absorption). From the model, the apparent blackbody temperature ($T_{\rm blackbody}$) and the normalization (equal to the square of the apparent radius R of the emission region) are obtained. The evolution of these parameters for each burst in our sample are shown in Figures 6–8 (note that the radius is normalized for a distance of 10 kpc; Muno et al. 2001). The resulting spectral parameters should be used with caution, because it is unlikely that the emission during the bursts is a pure blackbody (e.g., London, Taam, & Howard 1984). We refer to Muno et al. (2000) and references therein for a discussion about this.

From Figures 6 and 7 it is clear that all bursts with burst oscillations exhibit a RE episode during which the temperature decreases and the radius increases. However, for the bursts which exhibit the oscillations in the rise (Fig. 6), this episode starts later in the bursts (>1 seconds after the start of the burst) than for the bursts which exhibit the oscillations in the burst tail (Fig. 6; <1 seconds). Although we have only a limited number of bursts this correlation is strict. In the bursts which exhibited burst oscillations in the tail, the oscillations only appeared after the radius expansion episode already had ended.

Of the three bursts which do not exhibit burst oscillations (Fig. 8), only one (burst 7) exhibits a RE episode. However, this RE episode begins very early on in the burst and this unusual behavior might be related to its lack of burst oscillations. However, as already explained above, this burst also exhibits a slight count rate excess approximately 4 seconds after the start of the burst (see Fig. 5; see also Wijnands et al. 2001). It is of course possible that all unique properties of this burst are caused by the same underlying mechanism.

Burst 4 was identified by Wijnands et al. (2001) as unusual because of the frequency behavior of the oscillations during this burst. Normally when the oscillations were found in the tail of the bursts, their frequency increased slightly by 0.5–1 Hz (over a time span of a few seconds). For burst 4, the oscillations also increased first by $\sim$1 Hz before they died away. However, about 4 seconds later they reappeared again but at a frequency almost 5 Hz larger (see Fig. 3 of Wijnands et al. 2001). Our spectral analysis of this burst (Fig. 7 *top right*) does not show anything unusual at the time of the reappearance of the oscillations. The reason for this reappearance of the oscillations in

this particular burst and not in the other bursts remains therefore elusive.

4. Discussion

We have made a detailed study of the burst behavior of the neutron star X-ray transient MXB 1659–298. Due to the limited amount of data, bursts were only observed at relatively high inferred mass accretion rates. Thus, a detailed investigation of the burst behavior versus accretion rate as had been done for KS 1731–260 (Muno et al. 2000) and 4U 1728–34 (Franco 2001; van Straaten et al. 2001) could not be performed. However, consistent with those studies, we find that at high inferred mass accretion rates (on the atoll source banana branch), the bursts can exhibit burst oscillations, although several bursts were observed at similar accretion rates, which do not exhibit such oscillations.

Muno et al. (2001) briefly checked the color-color diagrams of all the burst oscillation sources known (including MXB 1659–298, but excluding MXB 1743–29 because source confusion made it very difficult to isolate the persistent emission from this source), and they reported that the bursts which exhibited oscillations all occurred at relatively high mass accretion rates. However, due to the lack of observations at low accretion rate for all sources besides KS 1731–260 and 4U 1728–34 (Muno et al. 2000; Franco et al. 2001; van Straaten et al. 2001), it is possible that burst occurring at relatively low mass accretion rates in those sources, might still exhibit such oscillations. In this respect it is interesting to note that for the X-ray transient SAX J1808.4–3658, burst oscillations might have been seen (in 't Zand et al. 2001), but only when the source was at very low luminosity (too low to be detected with the Wide Field Cameras aboard *BeppoSAX*). Therefore, if these oscillations are due to the same phenomenon as the burst oscillations seen in the other sources, then for SAX J1808.4–3658 the burst oscillations are seen when the source is in its low-luminosity state, contrary to what has been observed so far for the other sources. However, it has been suggested (Psaltis 2001) that the oscillations seen for SAX J1808.4–3658 are different from the burst oscillation phenomenon and that they might be related to same mechanism which produces the millisecond pulsations in the persistent X-ray emission of this source (Wijnands & van der Klis 1998).

Franco (2001) noticed that for 4U 1728–34, the bursts with oscillations in the decay phase only occurred at mass accretion rates lower than those bursts for which the oscillations were seen either throughout the bursts or only during their rising phase. For MXB 1659–298, we do not see such a correlation: bursts with the oscillations in the decay phase (e.g., bursts 3 and 4) can occur at the same mass accretion rates as those with the oscillations only in the rise (e.g., burst 2). It is interesting to note that the burst which occurred at the highest inferred mass accretion rate (burst 11), exhibited oscillations only during its rising phase. Currently, not enough data are available for any of the burst oscillation sources to determine whether the correlation found by Franco (2001) was a coincidence; that it only applies to 4U 1728–34; or that it is valid for more burst oscillation sources.

Besides the burst oscillations, the correlations of the other burst properties (e.g., the rise and decay times, radius expansion episodes) with the mass accretion rate for MXB 1659–298 are also not so clean as for KS 1731–260 (Muno et al. 2000) and 4U 1728–34 (Franco 2001; van Straaten et al. 2001). For example, for MXB 1659–298, bursts with and without episodes of radius expansion can occur at very similar mass accretion rate. In this respect, MXB 1659–298 is more similar to Aql X-1 (Fox et al. 2001) than to KS 1731–260 or 4U 1728–34. However, the bursts in both Aql X-1 and MXB 1659–298 have so far only been detected at a rather limited mass accretion rate range (especially compared to the other two sources). It might be possible that in such a small range, the burst properties are not so well correlated with the mass accretion rate, but that cleaner correlations will arise when bursts are observed over a larger range of mass accretion rates.

Muno et al. (2000) divided the bursts in KS 1731–260 in two distinct groups: those bursts which exhibited burst oscillations, high peak fluxes, short decay times, and episodes of radius expansion, and those bursts which did not show oscillations, had low peak fluxes, had longer decay times, and exhibited no episodes of radius expansion. Muno et al. (2000) associated the first group with helium rich bursts and the second group with hydrogen rich bursts. The MXB 1659–298 bursts are not completely consistent with this division, although they follow a similar trend for those which exhibited bursts oscillations: in general those bursts have high peak fluxes (except for burst 11 which is relatively dim), have episodes of radius expansion, and have relatively short decay times. The bursts which do not exhibit burst oscillations do not follow the KS 1731–260 division so strictly. Burst 6 is the dimmest in our sample and has no radius expansion episode, but it does have a relatively short decay time; burst 7 has no oscillations but it is rather bright and has a short decay time; burst 13 has no RE episode and it has the longest decay time of all our bursts, but it is still as bright as the bursts which exhibited burst oscillations.

Despite these differences between the burst behavior in KS 1731–260 and MXB 1659–298, those two sources are more similar to each other than MXB 1659–298 is to 4U 1728–34. In 4U 1728–34, the bursts which exhibited burst oscillations are equally like to have or not to have RE episodes (Franco 2001; van Straaten et al. 2001). All the bursts in our example which show oscillations also exhibited RE episodes. The burst oscillations in 4U 1728–34 occur in the dimmest bursts, again contrary to what we observe for MXB 1659–298. The fact that MXB 1659–298 is more similar to KS 1731–260 in its bursting behavior than to 4U 1728–34 might be related to the fact that the burst oscillation frequency of KS 1731–260 and MXB 1659–298 are very similar (524 Hz vs. 567 Hz), compared to 363 Hz for 4U 1728–34.

Recently, Muno et al. (2001) noticed that for the "fast oscillators" (those sources which have burst oscillations with frequencies above 500 Hz), the burst oscillations are predominantly observed in bursts which also exhibit radius expansion episodes. For the "slow oscillators" (burst oscillations frequency $\sim$300 Hz), the oscillations are equally likely to be found in bursts with and without radius expansion episodes. The bursts reported for MXB 1659–298 in the present study were also used by Muno et al. (2001), so we cannot conclude anything further from our present work about this correlation. However, Muno et al. (2001) included all the bursts which occurred during the dips

and the eclipses, so their numbers for MXB 1659–298 are possibly effected by the effects of those events on the measured bursts parameters (e.g., if the dips prevent one from seeing oscillations or if they change the apparent spectral parameters of the bursts). If we only use the bursts outside the dips and eclipses, the correlations found for this source become even stronger. All five bursts which exhibit burst oscillations also have a radial expansion episode. Two of the three bursts which do not show oscillations do not exhibit radial expansion, and only one burst remains which exhibits radius expansion but no burst oscillations.

When comparing the accretion history of the fast rotators with the slow rotators (as defined by Muno et al. 2001), a remarkable, although not a strict, correlation can be found. All of the three known slow rotators (4U 1728–34, 4U 1702–429, 4U 1916–053) are persistent sources. In contrary, at least four out of the six fast rotators are transients (4U 1608–52, MXB 1659–298, Aql X-1, and KS 1731–260) and only one source is clearly persistent (4U 1636–53; the other source still has conclusively to be identified with MXB 1743–298, which might be a persistent source). This difference between the fast and slow rotators might be related to their different burst behavior as observed by Muno et al. (2001). The neutron star crust and interior will be different for the transient systems compared to the persistent systems. The neutron stars in the transients are most likely cooler than in the persistent systems, which will affect their burst behavior (e.g., Fujimoto et al. 1984; see Lewin et al. 1993 for a discussion and further references).

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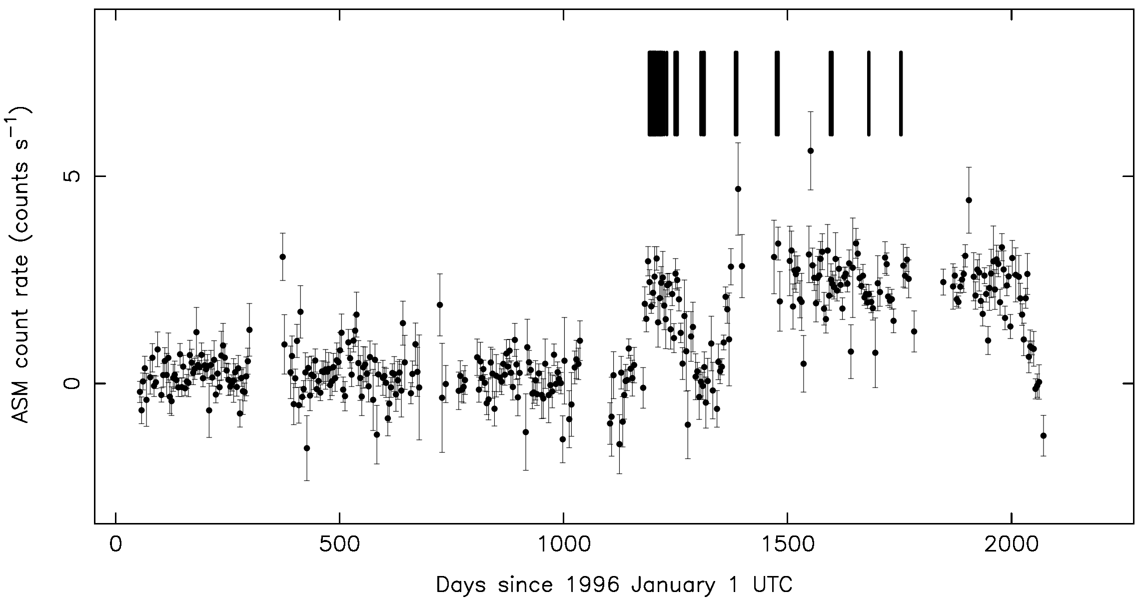


Fig. 1.— The *RXTE*/ASM light curve (1–12 keV) of MXB 1659–298 up to 5 September 2001. The data points have been rebinned into 4 day bins. The solid lines are the times of the *RXTE*/PCA observations.

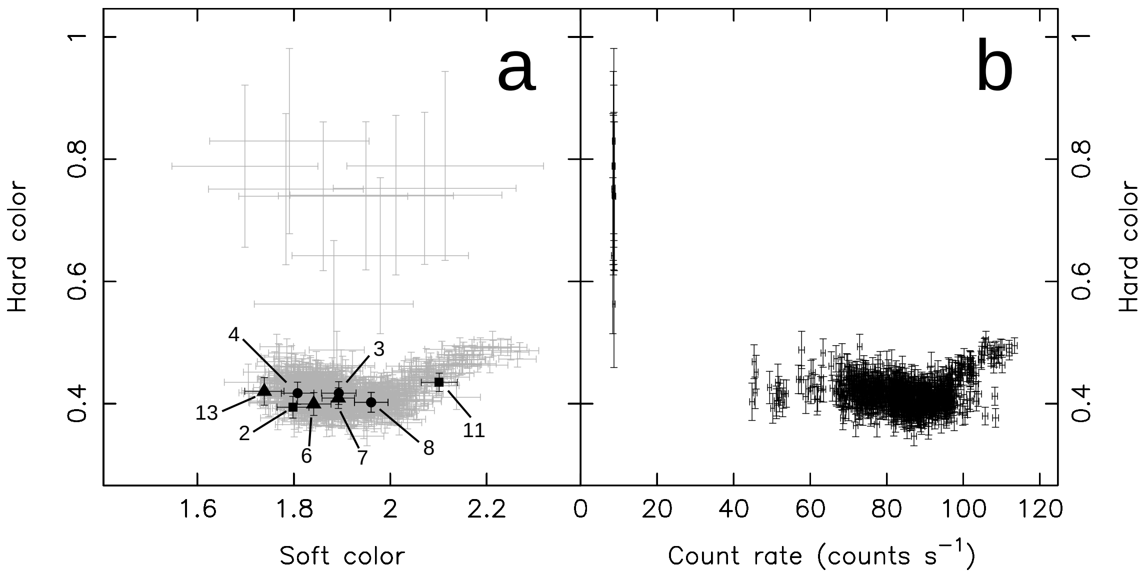


Fig. 2.— The color-color diagram (a) and the hardness-intensity diagram (b) of MXB 1659–298. The data were from PCU 2 only with the dips and eclipses excluded. The time resolution of the data is 256 seconds. In (a) the bursts are indicated by number (according to Wijnands et al. 2001). Solid circles indicate the bursts for which oscillations were detected in the tail of the burst, the solid squares the ones for which oscillations were found in the rise, and solid triangles those for which no oscillations could be detected. The soft color is the count rate ratio between 4.1–7.5 keV and 2.9–4.1 keV, the hard color the ratio between 11.4–18.8 keV and 7.5–11.4 keV, and the count rate is between 2.9 and 18.8 keV. The count rates were background subtracted but not dead-time corrected.

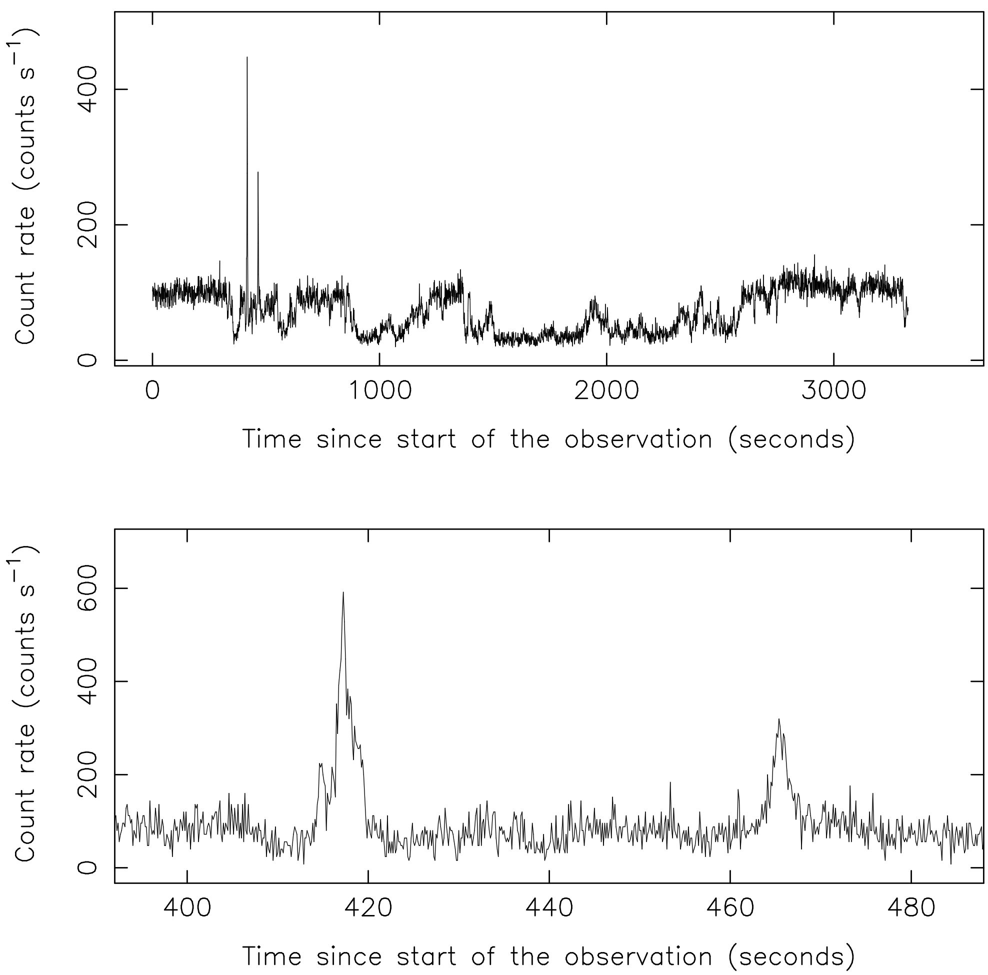


Fig. 3.— The light curves of the bursts during observation 40050-04-09-01. The top panel shows the light curve of the total observation, which clearly shows the dipping activity of the source; the bottom panel shows a close-up of the two bursts. The count rates are for 1 PCU, 2–60 keV, and are not background subtracted or dead time corrected. The time resolution is 1 second in the top panel and 0.125 seconds in the bottom panel.

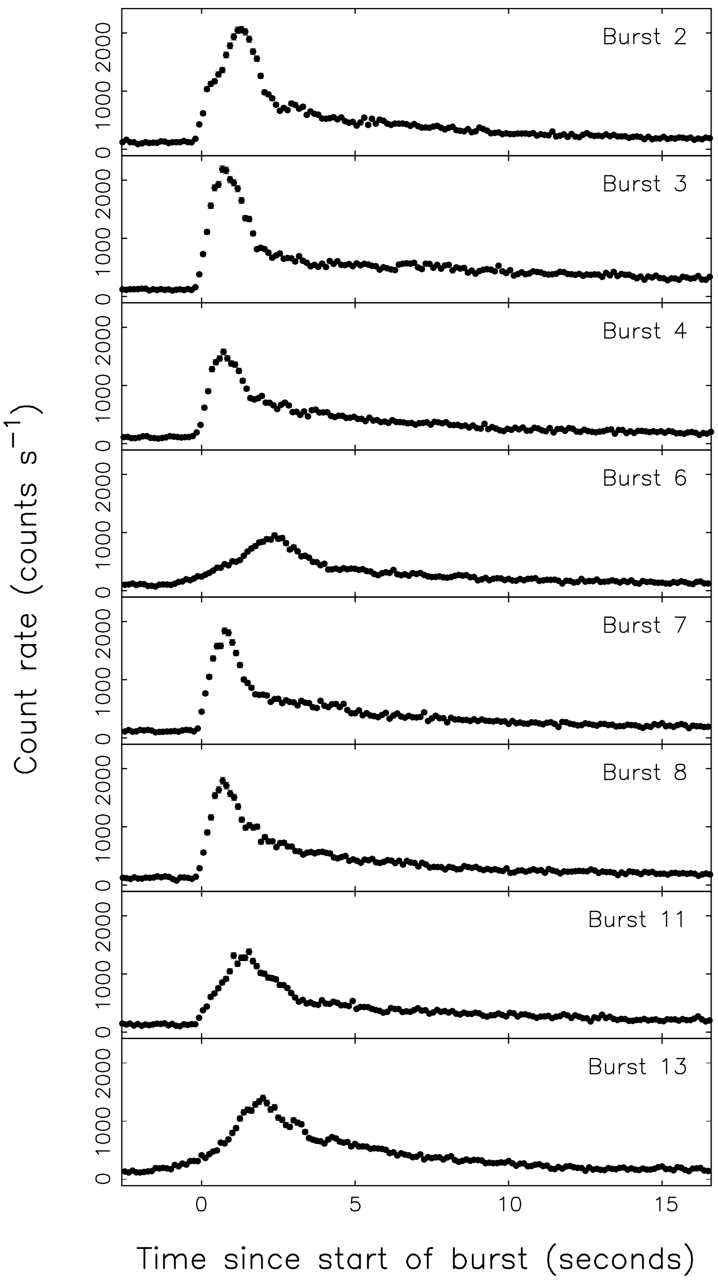


Fig. 4.— The *RXTE*/PCA light curves of the bursts of MXB 1659–298. The data points are 1/8 seconds bins. The count rates are for 2–60 keV, for 1 detector, and are not background subtracted or dead time corrected. Time is from the start of the bursts, which is defined as the time when the count rate reached a level of 25% of the peak count rate. For bursts 2 and 11 the burst oscillations were found only during the rise of the bursts. For burst 3, 4, and 8 the oscillations were only found in the tail of the bursts. No oscillations were found for bursts 6, 7, and 13.

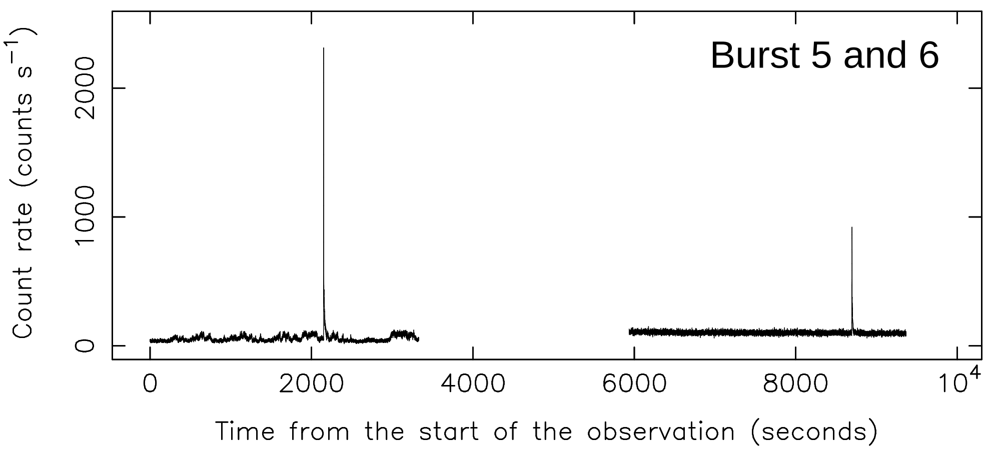


Fig. 5.— The light curves of bursts 5 and 6. The count rates are for 1 detector, 2–60 keV, and are not background subtracted or dead time corrected. The time resolution is 0.25 seconds.

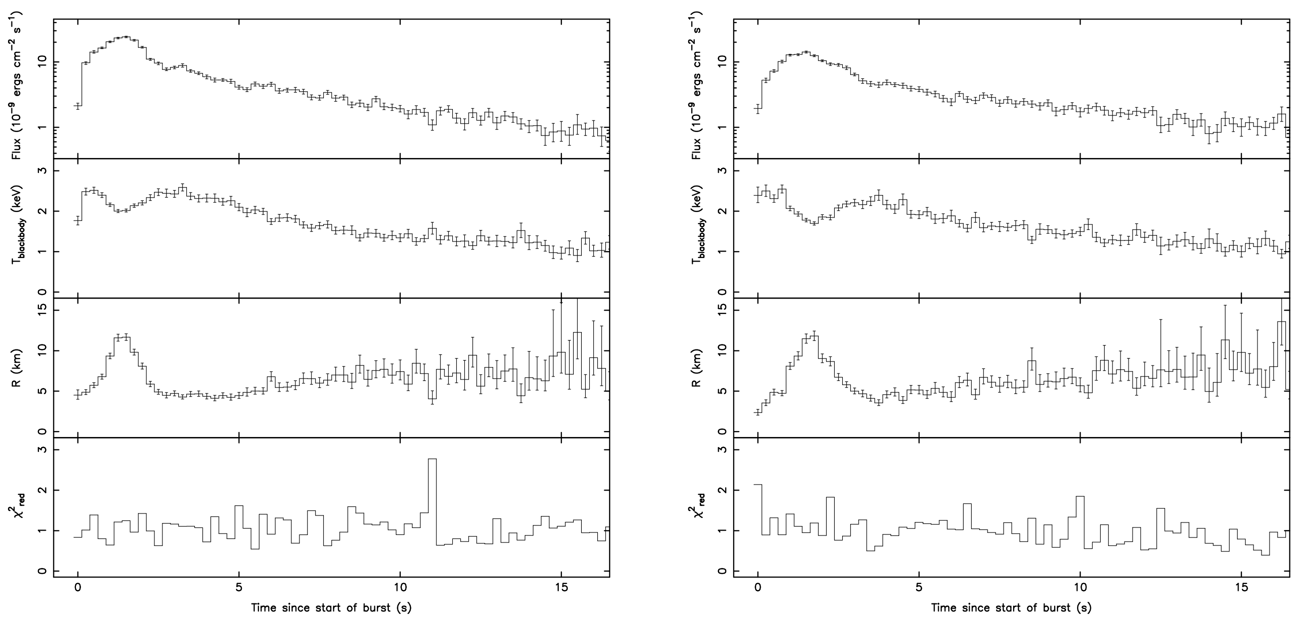


Fig. 6.— The burst parameters versus time for the bursts which exhibit burst oscillations only during the rise of the bursts (burst 2 [*left*] and burst 11 [*right*]). The error bars represent 90% confidence intervals. The flux is the bolometric flux. The radii are estimated for an assumed distance of 10 kpc.

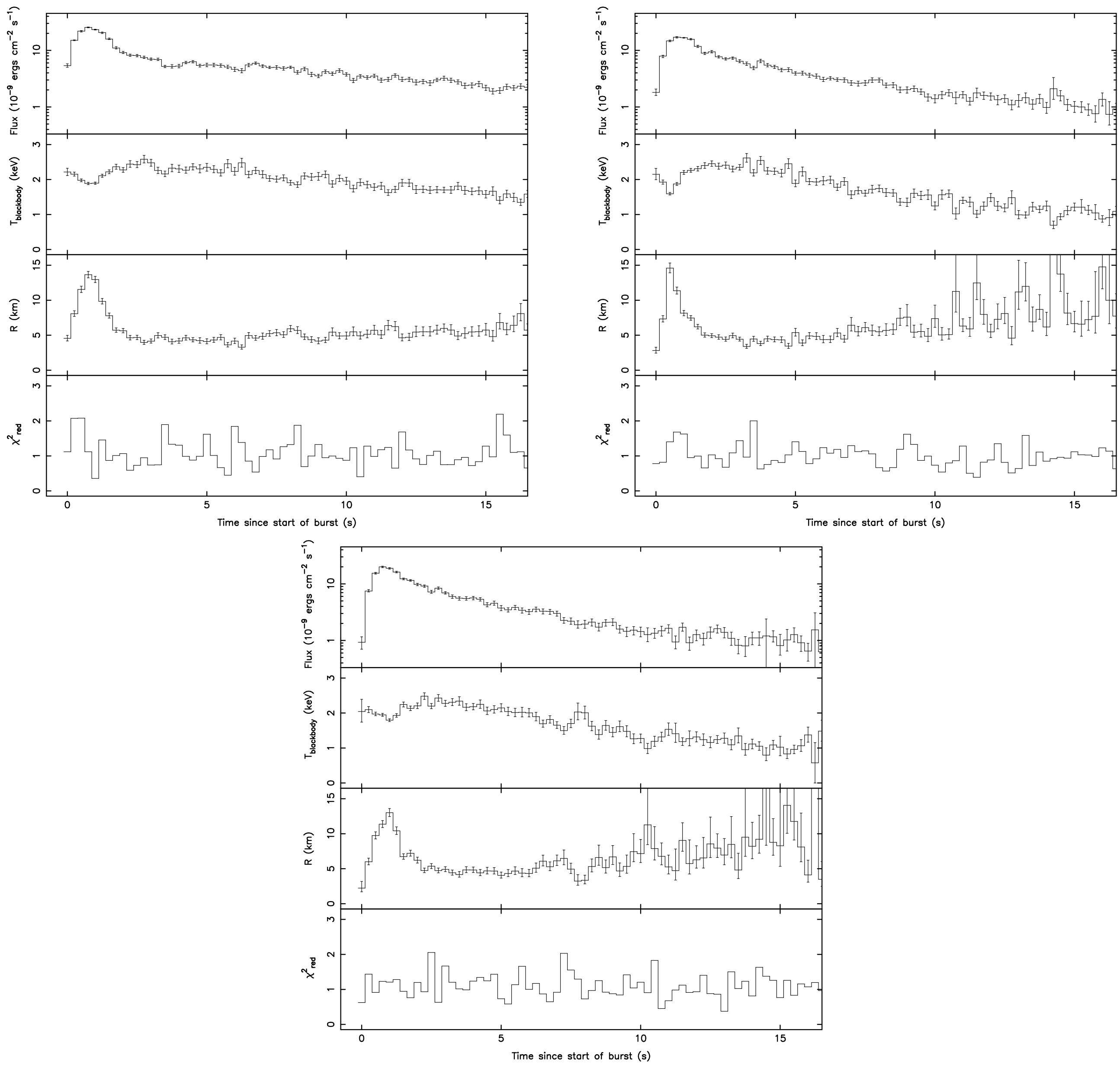
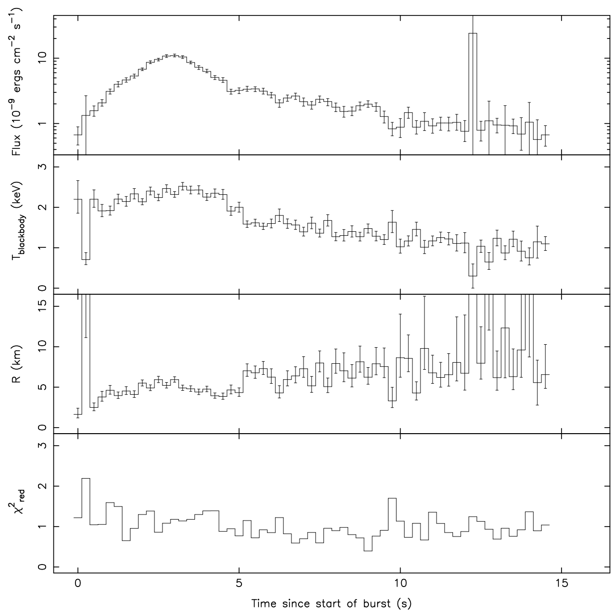
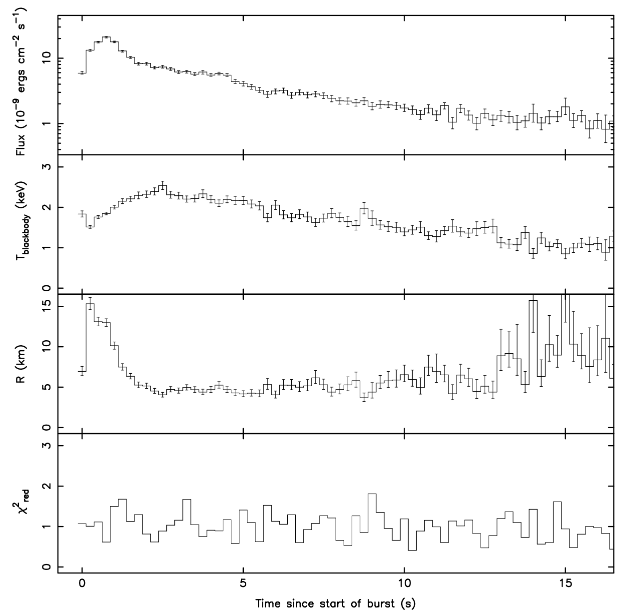


Fig. 7.— The burst parameters versus time for the bursts which exhibit burst oscillations only during the tail of the bursts (burst 3 [*top left*], burst 4 [*top right*], and burst 8 [*bottom*]). The error bars represent 90% confidence intervals. The flux is the bolometric flux. The radii are estimated for an assumed distance of 10 kpc.





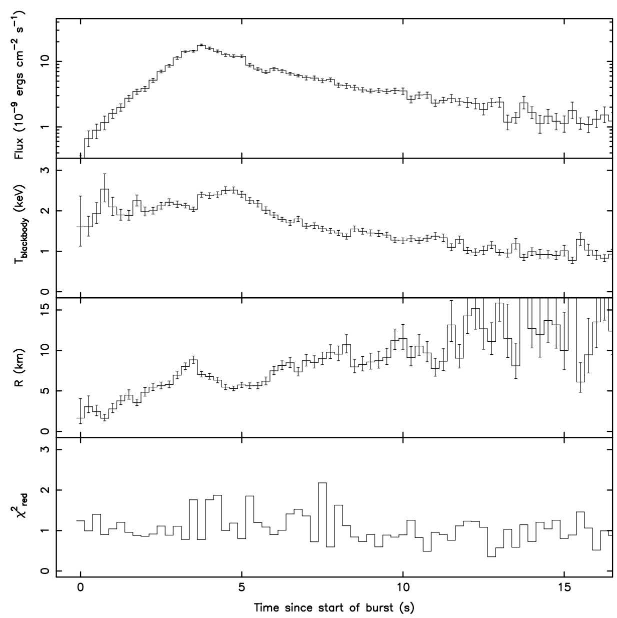


Fig. 8.— The burst parameters versus time for the bursts which did not exhibit burst oscillations (burst 6 [*top left*], burst 7 [*top right*], and burst 11 [*bottom*]). The error bars represent 90% confidence intervals. The flux is the bolometric flux. The radii are estimated for an assumed distance of 10 kpc.

Table 1. The properties of the X-ray bursts

$\#^a$	Peak count rate^a (counts s^{-1} PCU^{-1})	Peak flux^b (10^{-9} erg cm^{-2} s^{-1})	$t^c_{\rm rise}$ (s)	$t^d_{\rm decay,1}$ (s)	$t^d_{\rm decay,2}$ (s)	Osc.^{a}	RE episode	Persistent flux^e (10^{-10} erg cm^{-2} s^{-1})
2	2060	24.2±0.8	1.0	0.51±0.04	6.9±0.3	Rise	Yes	8.9
3	2190	25.5±0.5	0.6	0.57±0.03	12.5±0.3	Tail	Yes	8.9
4	1580	17.1±0.6	0.5	0.50±0.04	7.3±0.2	Tail	Yes	8.6
6	950	10.9±0.6	2.0	0.7±0.2	5.9±0.4	No	No	8.1
7	1840	21.1±0.7	0.7	0.37±0.02	6.8±0.2	No	Yes	9.3
8	1800	20.0±0.7	0.5	1.0±0.2	7.8±0.6	Tail	Yes	9.7
11	1385	14.2±0.5	1.4	0.98±0.07	9.4±0.4	Rise	Yes	10.6
13	1520	17.7±0.7	1.7	3.0±0.2	15±2	No	No	5.8

[a]See Wijnands et al. 2001 for the numbering of the bursts, their peak count rate (2–60 keV), and if and when the burst ocillations occured.

[b]The bolometric peak flux of the bursts.

[c]The rise time of the bursts. Defined as the time it takes for the flux to increase from 25% to 90% of the peak flux.

[d]Exponential decay times of the bursts; $t_{\rm decay,1}$ is the decay time for the first exponential and $t_{\rm decay,2}$ for the second one.

[e]Absorbed 3–25 keV flux, just prior to the onset of the bursts. The model used to obtain those fluxes was an absorbed cut-off power-law with photon index of 1–1.5 and a cut-off energy of 5–6 keV. The assumed column density was 0.2×10^{22} cm^{-2}.